

WHAT IS CLAIMED IS:

1. An off-line feed rate scheduling method of a CNC machining process that is performed according to workpiece geometry and a given set of NC code provided from a CAD/CAM system, the method comprising:

5 selecting a constraint variable and inputting a reference value related to the constraint variable;

estimating a cutting configuration where a maximum constraint variable value (CVV) occurs through ME Z-map modeling;

10 obtaining the estimated cutting configuration and estimating a specific rotation angle (ϕ_s) where the maximum constraint variable value occurs through constraint variable modeling;

calculating a feed rate that satisfies the reference value of the constraint variable at the estimated specific rotation angle; and

applying the calculated feed rate to the NC code.

15 2. The method of claim 1, wherein the calculating a feed rate comprises:

inputting specific feed rates f_1 and f_2 ($f_1 < f_2$);

calculating maximum constraint variable values CVV_1 and CVV_2 corresponding to the feed rates f_1 and f_2 , respectively, at the specific rotation angle;

20 approximating a feed rate f_{next} that corresponds to a reference value RV of a constraint variable value using the formula,

$$f_{next} = f_1 + \frac{(RV - CVV_1)(f_2 - f_1)}{CVV_2 - CVV_1};$$

calculating a constraint variable CVV_{next} in the case where the feed rate is f_{next} ; and

25 determining using the formula below if the constraint variable value CVV_{next} when compared to the reference value RV is less than an error limit, applying the feed rate f_{next} to the NC code when it is less than the error limit, replacing the feed rate f_2 by f_{next} and repeating the process of obtaining f_{next} when this value is not less than the error limit and the reference value RV is greater than the constraint variable value CVV_{next} , and replacing the feed rate f_1 by f_{next} and repeating the process of obtaining
30 f_{next} when this value is not less than the error limit and the reference value is not greater than the constraint variable value CVV_{next} ,

where

$$\frac{CVV_{next} - RV}{RV} < \text{Error Limit}$$

3. The method of claim 1, wherein computing cutting configurations through ME Z-map modeling comprises:

searching for node points located in a cutting area;

identifying whether a target node is an edge node (a node closest to a cutter edge) or not;

calculating and updating a height value of each node in the cutting area;

moving a target node if it is an edge node and storing movement direction angles;

computing the cutting configurations using the stored angles.

4. The method of claim 3, wherein the cutting configurations computed through ME Z-map modeling include an entry angle, an exit angle, an axial depth of cut and so on.

5. The method of claim 3, wherein in the case where a difference between a distance from a tool center to a target node and a tool radius is smaller than a movement limit, this node is designated as an edge node.

6. The method of claim 1, wherein one of cutting force and machined surface error is selected as a constraint variable.

7. An off-line feed rate scheduling method for adjusting a cutting force of a CNC machining process that is performed according to workpiece geometry and a given set of NC code provided from a CAD/CAM system, the method comprising:

inputting a reference cutting force;

estimating a cutting configuration where a maximum cutting force occurs through ME Z-map modeling;

receiving the estimated cutting configuration and estimating a specific rotation angle where the maximum cutting force occurs through cutting force modeling;

calculating a feed rate that satisfies the reference cutting force at the estimated specific rotation angle; and

applying the calculated feed rate to the NC code.

8. The method of claim 7, wherein the reference cutting force is selected from a reference cutting force RF_1 established to prevent breaking of a tool shank, and a reference cutting force RF_2 established to prevent damage to an edge portion of a tool,

RF₁ and RF₂ being calculated by the formulae

$$RF_1 = SF \cdot TRS \cdot S_1$$

$$RF_2 = SF \cdot TRS \cdot S_2$$

where RF₁ represents the reference cutting force considered to avoid breakage of tool shank and RF₂ indicates the reference cutting force to prevent breakage of tool edge; SF means safety factor, which is used to make up for unpredictable factors such as cutter geometry error or cutter material variation; and TRS means transverse rupture strength of the tool material.

9. The method of claim 7, wherein the tool is a flat end milling tool, and cutting force components of each direction according to a rotational angle of the tool are obtained using

$$F_x(j) = \sum_k \sum_l F_x(i, j, k)$$

$$F_y(j) = \sum_k \sum_l F_y(i, j, k)$$

$$F_z(j) = \sum_k \sum_l F_z(i, j, k)$$

where

$$F_x(i, j, k) = [C_1 K_n \cos(\phi - \alpha_r) + K_f K_n C_3 \cos \phi - K_f K_n C_4 \sin(\phi - \alpha_r)] t_c(\phi) B_1$$

$$F_y(i, j, k) = [C_1 K_n \sin(\phi - \alpha_r) + K_f K_n C_3 \sin \phi + K_f K_n C_4 \cos(\phi - \alpha_r)] t_c(\phi) B_1$$

$$F_z(i, j, k) = [-C_2 K_n + K_f K_n C_5] t_c(\phi) B_1$$

and where C₁, C₂, C₃, C₄, and C₅ in the above are calculated by the following:

$$C_1 = \frac{\cos \theta_h}{\sin \theta_{th}}, \quad C_2 = \frac{\sin \theta_h}{\sin \theta_{th}} \cdot \cos \alpha_r$$

$$C_3 = \sin \theta_h (\sin \theta_c - \cos \theta_c \cot \theta_{th})$$

$$C_4 = \frac{\cos \theta_c}{\sin \theta_{th}}$$

$$C_5 = \cos \theta_h (\sin \theta_c - \cos \theta_c \cot \theta_{th})$$

and

$$\cos \theta_{th} = \sin \alpha_r \cdot \sin \theta_h$$

10. The method of claim 9, wherein K_n, K_f, and θ_c may be obtained by the following formulae,

$$\ln(K_n(i, j, k)) = A_1 - (A_1 - A_2)e^{-(A_3 t_c(i, j, k))^{A_4}}$$

$$K_f(i, j, k) = B_1 - (B_1 - B_2)e^{-(B_3 t_c(i, j, k))^{B_4}}$$

$$\theta_c(i, j, k) = C_1 - (C_1 - C_2)e^{-(C_3 t_c(i, j, k))^{C_4}}$$

5 11. The method of claim 7, wherein the tool is a ball end milling tool, and cutting force components of each direction according to a rotational angle of the tool are obtained using

$$\begin{Bmatrix} F_x \\ F_y \\ F_z \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \begin{Bmatrix} K_1 \\ K_2 \\ K_3 \end{Bmatrix}$$

where

$$K_1 = K_n$$

$$K_2 = \cos \theta_c K_n K_f$$

$$K_3 = \sin \theta_c K_n K_f$$

$$A_{11} = B_1 \sum_k \sum_i (\cos \alpha_r \cos \phi \cos \theta_h + \sin \alpha_r \sin \phi) \cdot t_c(\phi)$$

$$A_{12} = B_1 \sum_k \sum_i (\sin \alpha_r \frac{1}{f_2} \cos \phi \cos \theta_h - \frac{1}{f_2} \cos \alpha_r \sin \phi - \frac{f_1}{f_2} \cos \alpha_r \cos \phi \sin \theta_h) \cdot t_c(\phi)$$

$$A_{13} = B_1 \sum_k \sum_i (-\frac{f_1}{f_2} \sin \phi + \frac{1}{f_2} \cos \phi \sin \theta_h) \cdot t_c(\phi)$$

$$A_{21} = B_1 \sum_k \sum_i (\cos \alpha_r \sin \phi \cos \theta_h - \sin \alpha_r \cos \phi) \cdot t_c(\phi)$$

$$A_{22} = B_1 \sum_k \sum_i (\sin \alpha_r \frac{1}{f_2} \sin \phi \cos \theta_h + \frac{1}{f_2} \cos \alpha_r \cos \phi - \frac{f_1}{f_2} \cos \alpha_r \sin \phi \sin \theta_h) \cdot t_c(\phi)$$

$$A_{23} = B_1 \sum_k \sum_i (\frac{f_1}{f_2} \cos \phi + \frac{1}{f_2} \sin \phi \sin \theta_h) \cdot t_c(\phi)$$

$$A_{31} = B_1 \sum_k \sum_i (-\sin \theta_h \cos \alpha_r) \cdot t_c(\phi)$$

$$A_{32} = B_1 \sum_k \sum_i (-\sin \alpha_r \frac{1}{f_2} \sin \theta_h - \frac{f_1}{f_2} \cos \alpha_r \cos \theta_h) \cdot t_c(\phi)$$

12. The method of claim 11, wherein K_n , K_f , and θ_c may be obtained by the following formulae:

$$K_n = K_1$$

$$\theta_c = \tan^{-1} \left(\frac{K_3}{K_2} \right)$$

$$K_f = \frac{K_2}{\cos \theta_c K_n}$$

5 13. An off-line feed rate scheduling method for adjusting a machined surface error of a CNC machining process that is performed according to workpiece geometry and a given set of NC code provided from a CAD/CAM system, the method comprising:
inputting a reference surface error;

estimating a cutting configuration where a maximum surface error occurs through ME Z-map modeling;

receiving the estimated cutting configuration and estimating a specific rotation angle where the maximum surface error occurs through machined surface error modeling;

calculating a feed rate that satisfies the reference surface error at the estimated specific rotation angle; and

applying the calculated feed rate to the NC code.

14. The method of claim 13, wherein the tool is a flat end milling tool, and a cusp error C_h is calculated using the formula

$$C_h = R - \sqrt{R^2 - \left(\frac{f_t}{2}\right)^2}$$

where R is a tool radius and f_t is an edge feed rate.

15. The method of claim 13, wherein the tool is a ball end milling tool, and a cusp error C_h is calculated using the formula,

$$C_h = R - \sqrt{R^2 - \left(\frac{D}{2}\right)^2}$$

where $D = \sqrt{(TPD)^2 + f_t^2}$, TPD being an interval between a tool path.